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COMBINED EFFECT OF MICROWAVE FIELD AND FOCUSED LASER RADIATION ON DIELECTRICS

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The combined effect of a microwave electric field and focused laser radiation on dielectrics is investigated with respect to developing a method for electric-discharge treatment. This idea is based on the fact that the absorption of microwave radiation by dielectrics increases when they are previously heated using an additional heat source. Due to this phenomenon, the destruction zone on the dielectric surface can be more narrow than the preheated area.

Electric-discharge treatment of materials is a promising approach to solving various engineering problems in machine building. Although many variants of discharge technology exist, their application area is limited to conducting materials, since the treated part should act as one of the electrodes participating in the discharge.

Dielectric materials require this kind of discharge treatment when they are especially hard and cannot be easily treated by other methods. Electrode-free discharges are especially promising for treatment of dielectrics. It is proposed to use variable fields of the radio and microwave frequency ranges.

It is expected that the microwave discharge or, more precisely, the effect of a high-intensity microwave field can be used to treat dielectric materials. The concept of microwave treatment is based on the effect of local absorption of microwave power by a dielectric and its subsequent destruction due to intense heating. In doing so, discharge does not necessarily arise in each case. However, experiments indicate that the problem of concentrated microwave power needed to produce narrow incisions and fine relief, on a sufficiently small surface area which requires treatment, is yet unresolved [1]. The main difficulties are related to the limitation with respect to focusing the radiation emitted by the waveguide. It is recommended in [1] to use radiation with as small a wavelength as possible.

Experiments with 3-mm microwave radiation demonstrated perceptible absorption of power by a dielectric with a depth comparable to the wavelength. Good results were obtained in powder sintering or ceramic surface doping. However, such operations as cutting, drilling, etc., apparently cannot be successfully accomplished.

Localization of microwave power with a significantly greater wavelength (about 12.5 cm) on a dielectric surface employing a metallic rod was experimentally tested in our previous investigations. Local discharges were registered in a forevacuum (about 133.3×10^{-2} Pa) on alundum ceramics, as the consequence of using a rod which concentrated the electric field on a small site of the ceramic surface. The discharge produced shallow (0.3 – 0.5 mm deep) craters 2 – 3 mm in diameter after 4 – 5 min of operation. However, the craters were of poor quality, as they had rather sloping walls and a rib on the edges. The visually observed size of the discharge area is comparable to the distance between the rod and the ceramic material.

Preliminary results showed that it is necessary to find and investigate other additional methods to localize the effect of microwave radiation on ceramics, since the shallow holes on the surface are too far from being regarded as incisions or narrow openings in ceramics. The solution was prompted by certain studies of parasite discharges in waveguides. Papers [2, 3] reported the emergence of microwave discharges on local inclusions of extraneous materials in the near-surface layer of waveguide metal walls. This was attributed to the absorption of microwave power by the inclusion, its heating and evaporation (or gas desorption from the inclusion surface) leading to a break-down. It is obvious that the discharge localization and the size of the discharge area are determined by the inclusion size and the power absorption coefficient.

In searching for the mechanisms of localization of ceramic-treating discharges, it is possible to use the above effect and to develop some non-homogeneity of dielectric properties, similar to the initiation of parasite discharges in microwave guides. RF Patent No. 2024367 describes a

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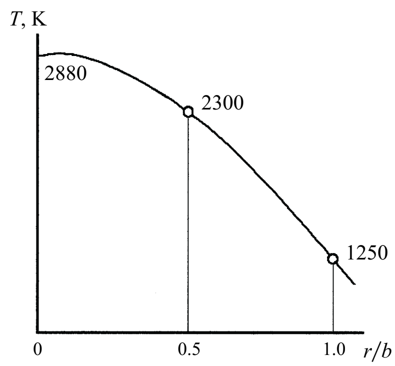

Fig. 1. Temperature distribution over the heated spot.

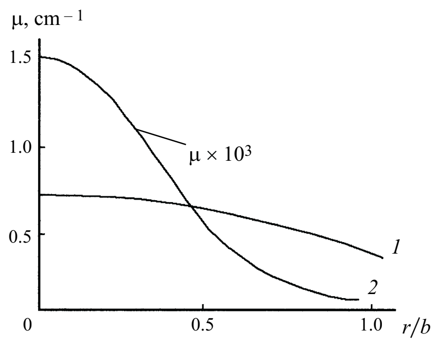

Fig. 2. Radiation absorption coefficient μ versus radius r of the heated area for wavelengths of 0.3 cm (*1*) and 12.5 cm (*2*).

method for the development of functionally similar “inclusions” or, more exactly, “marks” on the dielectric surface for subsequent microwave discharge treatment. The present paper describes the results of the formation of “marks” on the surface of alundum ceramics using a thermal pulse in the presence of a microwave field.

The process is based on the known relationship between the absorption of microwave radiation μ by a dielectric and the latter’s temperature, which is often approximated for a great number of dielectrics as

$$\mu = \mu_0 \exp(-A/T), \quad (1)$$

where μ_0 is the pre-exponential factor; A is a coefficient proportional to the activation energy of the absorption of electromagnetic oscillation energy by the dielectric, K; T is the temperature, K.

A thermal mark can be made using a narrow light beam. A laser beam was used in the experiments. If the radial energy distribution in the beam has the Gaussian form

$$q(t, r) = q_0(t) \exp(-r^2/b^2),$$

where q is the thermal flow density, W/m^2; t is the time, sec; r is the radial coordinate of the beam; q_0 is the energy density in the beam center; b is the beam width parameter, cm, then the temperature distribution over the surface of the half-space of the material has the form:

$$T(r, t) = T_0 + \frac{q_0 b^2 a}{\lambda\sqrt{\pi}} \int_0^t \frac{d\tau}{\sqrt{\tau}} \frac{\exp[-r^2/(4a^2\tau + b^2)]}{4a^2\tau + b^2}, \quad (2)$$

where $a^2 = \lambda/c\rho$ is the temperature conductivity (ρ is the density; c is the material heat capacity; λ is the thermal conductivity, W/(m · K)); τ is the time shift; T_0 is the initial temperature taken as homogeneous for the half-space.

The temperature in the center of the circular heated area is determined from the ratio:

$$T(0, t) = T_0 + \frac{q_0 b}{\lambda\sqrt{\pi}} \arctan\frac{2a\sqrt{t}}{b}.$$

For the purpose of the strong localization of microwave radiation absorption, it is necessary to ensure a narrow temperature distribution $T(r, t)$ within a certain time interval. Moreover, if the temperature distribution is substituted in relationship (1), it is possible to obtain an even more narrow distribution of the absorption coefficient $\mu(T)$. The calculations indicate that this can be accomplished in the case of a sufficiently great value of the parameter A, i.e., the dependence of the microwave radiation absorption coefficient on the dielectric temperature should be sufficiently strong.

Figure 1 shows the temperature distribution on the surface of alundum ceramics after heating for 2×10^{-4} sec with a laser beam radius $b = 10^{-2}$ cm and $q_0 = 5 \times 10^4$ W/cm^2, as follows from equation (2). If the microwave field is switched on at this moment, its energy will be nonuniformly absorbed in accordance with the temperature distribution based on the relationship $\mu(T)$, which is shown in Fig. 2, exhibiting two curves for two wavelengths, since the dielectric losses in ceramics depend on the wavelength of microwave radiation. Comparison of the curves shows that the overall absorption is greater in the case when the radiation wavelength is 0.3 cm. This is one of the reasons for the statement in [1] that the specified range is the most promising for material treatment. However, Fig. 2 exhibits good spatial selectivity for wavelength 12.5 cm, which makes the application of this wavelength more attractive for precise treatment of ceramics, although under temperatures suitable for treatment μ has relatively lower values. Therefore, precise treatment ought to be carried out using radiation at lower frequencies, although this decreases the process efficiency.

Simultaneous effects of the thermal pulse and absorbed microwave radiation cause the destruction of the marked site and evaporation of the material.

According to equation (1), the typical shape of the relationship between μ and T implies that thermal instability of the marked areas becomes possible if the microwave field is sufficiently intense. As a consequence, the instability results in the destruction of the marked areas. Therefore, under the

combined effect of two factors, a tendency for the removal of material from the marked area of the dielectric is observed. However, the instability can involve the material outside the marked area in the destruction process, since its mathematical model is similar to the model of explosion initiation by a hot ignition source [4]. According to this model, the hot source is a hemisphere of radius R indented into the half-space of the explosive material. The thermal energy of the explosive material is released as a result of the chemical reaction at a rate depending on T, according to conditions similar to those set by equation (1). A prerequisite to the initiation of a thermal explosion by a hot hemisphere with temperature T_1 is the fact of its radius reaching a certain critical value [4]:

$$R_{cr} = 3.48T_1\sqrt{\frac{\lambda}{q_m A\mu_0}}\exp\left(\frac{A}{2T_1}\right)\left[\ln\frac{A(T_1 - T_0)}{T_1^2}\right]^{0.3},$$

where q_m is the microwave power flow.

The estimates of R_{cr} for the values of q_m (about 2×10^3 W/cm^2) and T_1 (2500 – 3000 K) indicate that R_{cr} is within the range of several centimeters, since the parameters of alundum ($\mu_0 = 0.11$ cm^{-1} and $A = 12410$ K) in the case of relatively low frequencies, which are the most favorable for spatial selectivity, lead to a relatively low full absorption of microwave power. The marked area is significantly smaller (up to 1 mm across) than the estimated value of R_{cr}. On the other hand, the attainable values of q_m are limited (up to 5×10^3 W/cm^2) by the emergence of an electric discharge in air near the dielectric surface. Therefore, one should not expect a significant decrease in R_{cr} and, accordingly, a high probability of involving the material in the unstable state, since this would require high values of q_m (about 10^6 W/cm^2).

Thus, the thermal destruction of material as a result of the combined effect of the thermal pulse and the microwave power will not extend beyond the affected area after the thermal pulse is turned off. The imposition of the thermal mark can be used as a controlling factor in discharge treatment of dielectrics.

The combined action of a thermal pulse and microwave radiation on dielectrics was studied on an experimental set (Fig. 3). A ceramic sample was placed inside a microwave resonator which had a small opening in one of the walls. A pulse laser beam of about 15 W from aluminoyttrium garnet was directed through that opening into the resonator and focused on the sample surface employing a lens with a focus distance of 5 cm. The power of the microwave radiation source was 1100 W. However, this power was not effectively absorbed due to the low value of μ in cool samples, when the laser beam was not turned on. In this case, the sample had virtually room temperature.

On the other hand, the power of the focused laser beam was sufficient for local heating of the sample and making a hole up to 1 mm across, even if the microwave radiation was turned off (Fig. 4). When the microwave field in the resonator was turned on, much more intense interaction of the laser beam with the sample was observed (Fig. 5). Experiments were conducted with exposures of 1, 3, and 5 min. The difference between two profiles (with active and inactive microwave fields) was most clearly expressed under a short ex-

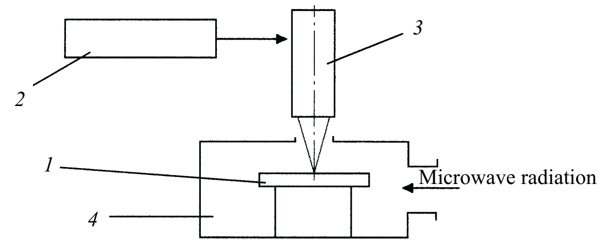

Fig. 3. Experimental set diagram: *1*) sample; *2*) laser; *3*) focusing device; *4*) resonator.

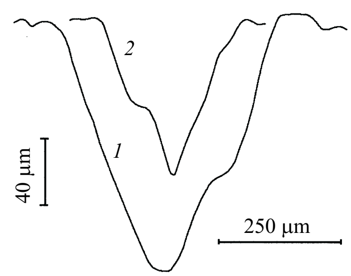

Fig. 4. Profiles of openings in ceramic samples produced with participation of microwave radiation (*1*) and without radiation (*2*).

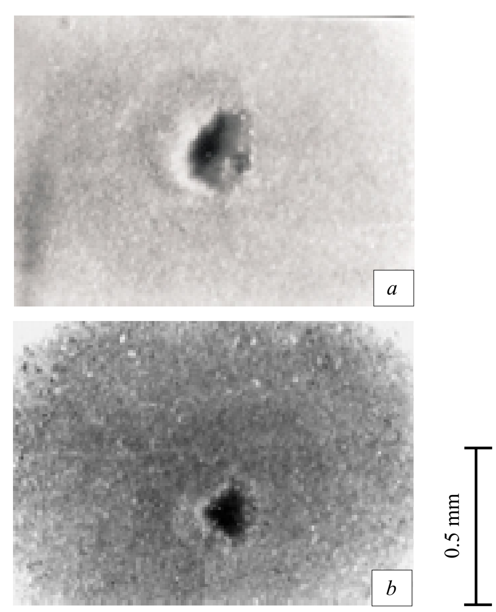

Fig. 5. Photomicrographs of holes made in ceramics by a laser with an active (*a*) and inactive (*b*) microwave field.

posure (1 min). Under two other exposures, openings with a larger diameter were produced due to the more prolonged laser action, but the possible effect of microwave radiation on the removal of material was less perceptible. According to the profile diagrams shown in Fig. 4, the application of the microwave field increased by at least 8 times the volume of the removed material under 1 min exposure. Longer exposures resulted in the emergence of cracks in the sample.

The considered model presumably does not fully correlate with the conditions of the experiment. In the theoretical model, the absorbed microwave radiation energy exceeded the energy supplied to the "marked" area employing a laser. In the experiment, the sample absorbed only a small part of the microwave power compared to the local supply of laser energy to the sample. In a certain sense, the two energy flows changed places in the course of treatment. The infliction of thermal marks using a laser beam becomes the main process in the removal of material from newly formed holes, and the microwave field assists in this process.

Apparently, the auxiliary role of microwave radiation is of a double nature. First, the microwave field performs additional heating of the material removed by the laser beam, due to the heightened absorption of the microwave power at the solid – vapor interface. Secondly, the microwave field initiates an electric discharge in the removed material vapor, which leads to the quick release of the vapor from the forming hole. The discharge initiation and its functioning could be visually observed. The quick vapor release from the emerging hole weakens the screening of the laser beam by vapor and thus accelerates the removal of material, whereas the principal energy contribution to the treated area is performed by the laser beam.

The present method of joint application of the microwave and laser radiation effects on dielectric materials appears promising for hard ceramics, which are difficult to treat by traditional cutting tools.

The method is not yet elaborated to the level of industrial use. So far, only the possibility of making incisions and holes, whose qualities are better than when using exclusively laser radiation, has been demonstrated. It was established that the rate of material removal increased 8 – 10 times due to using the additional microwave field.

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